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# Control of prehension in hemiparetic cerebral palsy: similarities and differences between the ipsi- and contra-lesional sides of the body

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**This study aimed at broadening our insight into ipsi- and contra-lesional control of prehension after unilateral brain damage. Six male adults with hemiparetic cerebral palsy (mean age 17 years 3 months, SD 15 months) performed unrestricted grasping of discs that differed in size (40, 60, and 80mm in diameter) and which were placed at different distances from the participants (150mm and 30mm). A precalibrated Optotrak 3020 system was used for recording motion. Kinematics of the transport and grasp component, and hand orientation at the moment of grasping, were determined. A marker on the wrist was used to calculate the kinematics of the transport component. The distance between the markers on the index finger and thumb was used for the calculation of the grasp component. Kinematic variables of the transport and grasp component were remarkably similar between both sides of the body. However, with the contra-lesional side, more time was spent in contact with the object before it was lifted, and movements were performed less fluently compared with the ipsi-lesional side. Maximum grasp aperture was attained very late during reaching. For final hand orientation, results showed a large standard deviation both within and between participants. These findings show that, despite the ostensible awkward prehension movements of the contra-lesional side (slowness and decreased fluency), similarities in the kinematics between both sides of the body are present, which may be indicative of intact central control of the movement. The results of variant final hand orientation, combined with the relative late occurrence of peak aperture, suggest that these participants encounter difficulties with forward planning and may use a step-by-step control strategy.**

In individuals with hemiparetic cerebral palsy (CP), i.e. unilateral brain damage acquired before, during, or after birth, the ability to perform a variety of daily activities is reduced. Research on the control of prehension movements in this participant group is, however, relatively scarce (see Steenbergen and Hulstijn 2001). Generally, CP results in spasticity, a condition that may be characterized as a velocity-dependent increase in tonic reflexes resulting in an excessive and awkward activation of skeletal muscles (Lance 1980, Barnes et al. 1994). Spasticity occurs in a variety of forms and severity levels that reflect the location, size, and timing of the cerebral lesion. Consequently, spasticity is associated with many symptoms, such as excessive coactivation of antagonistic muscles, hyperactive stretch reflexes, associated movements, stereotyped movement synergies, and hypertonia (Shumway-Cook and Woollacot 1995).

Currently, there is a debate as to whether the ostensibly awkward behavioural patterns that one can observe in atypical populations, such as those with hemiparetic CP, should be considered pathological or the result of adaptation processes (Latash and Anson 1996, Roby-Brami et al. 1997, Holt et al. 2000, Carson and Swinnen 2002, Levin et al. 2002, Steenbergen and Meulenbroek 2003). Importantly, our lack of knowledge about the basic principles of motor control seriously complicates a distinction to be made between what may be termed a disorder per se and the short- or long-term adaptation to this disorder (Gielen 1996, Latash and Anson 1996, Steenbergen and Meulenbroek 2003). Therefore, invariances and deviations in movement behaviour of atypical groups need to be meticulously researched in varying experimental conditions, so that the principles of (deviant) motor control are better understood and our knowledge of the disorder-adaptation issue may be advanced.

A ubiquitous feature of movement performance in hemiparetic CP is the presence of large timing differences between the ipsi- and contra-lesional sides (i.e. unimpaired and impaired respectively) of the body (Fisk and Goodale 1988; Brown et al. 1989; Sugden and Utley 1995; Utley and Sugden 1998; Steenbergen et al. 1996, 1998, 2000a). A meta-analysis in which unimanual hitting, reaching, and grasping movements were compared for ipsi- and contra-lesional sides of the body, showed an increase in manual asymmetries from hitting, to reaching to grasping (Van Thiel et al. 2000, Van Thiel and Steenbergen 2001). It was claimed that the larger timing differences could be attributable to the increased involvement of the more distal hand and finger musculature. Moreover, several studies showed an increased involvement of the proximal trunk and a decreased involvement of the more distal elbow in participants with hemiparesis compared with controls (stroke: Levin 1996, Cirstea and Levin 2000; CP: Steenbergen et al. 2000a; Van Roon et al. 2003, 2004).

Collectively, these findings suggest that the disorders at the more distal grasp component of the contra-lesional side are augmented, causing the large performance differences between both sides of the body. However, thus far, the characteristics of the grasp component of the contra-lesional side have not been studied, nor have the characteristics of the transport and grasp component been examined together in this group of participants (kinematics of the transport component for both limbs in hemiparetic CP: Steenbergen et al. 2000a; kinematics of the grasp component of the preferred hand in quadriplegic CP: Cope and Trombly 1998; kinematics of the ipsi-lesional side after stroke: Trombly 1993, Levin 1996, Hermsdörfer et al. 1999).

In the present study, we examined the kinematics of the transport and grasp component of both sides of the body to search for the invariances in kinematics that have repeatedly been reported in participants without disabilities. Examples of these invariances include influences of object location on the kinematics of the wrist transport (Jeannerod 1984, Gentilucci et al. 1991), and influences of object size on the kinematics of the grasp aperture (Wallace and Weeks 1988, Marteniuk et al. 1990, Kudoh et al. 1997, Paulignan et al. 1997). For example, Marteniuk et al. (1990), using ten discs differing in size, showed distinctive effects of disc size on grasp aperture. When participants without neuroimpairments had to grasp smaller discs, peak aperture was attained earlier and the amplitude of peak aperture was scaled to disc size, such that larger discs induced larger peak apertures. These authors argued that an increase in accuracy constraints of the task, by reducing disc size, is reflected in the timing of hand opening and closing.

Comparison of these previous findings in controls with participants of the present study may provide important insights into the principles guiding control of prehension that are unaltered after unilateral brain damage. In addition, similarities in the kinematics between both sides of the body in the participants of the present study may inform us about the central (re)organization of the underlying control structures after unilateral brain damage.

As well as deviations during movement execution, participants with hemiparetic CP also show deviations in the type of grip they use when they grasp an object. In participants without disabilities, there is ample evidence to suggest that optimization of end posture comfort is used as a constraint on grasp selection (Rosenbaum et al. 1992, 1996; Paulignan et al. 1997; Short and Cauraugh 1997, 1999). These findings suggest that the central nervous system strives for invariant end postures when grasps are planned. Contemporary studies in hemiparetic CP, however, indicate that these participants do not strive for such an invariant end posture as assessed by the type of grasp used (Hermsdörfer et al. 1999, Steenbergen et al. 2000b, 2004). These findings suggest difficulties in forward planning that these individuals encounter.

In the present study, we aimed to examine more specifically whether the number of hand orientations that these individuals use to grasp cylinders at various positions in the workspace is restricted, despite the numerous possibilities. This would indicate a process of forward planning for final hand orientation. Comparisons between both sides of the body would be made, as well as with findings in healthy controls, in a search for principles of movement planning that may have been altered after unilateral brain damage.

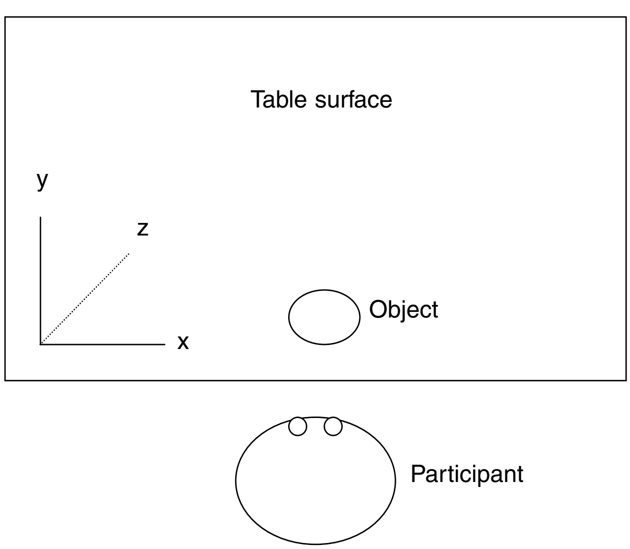


**Figure 1:** *Experimental set-up and definition of movement axes (view from above). The y-axis is the primary movement axis, where x-axis was used for calculation of final hand orientation.*

## Method

### PARTICIPANTS

Six male participants with CP (mean age 17 years 3 months, SD 15 months) and diagnosed with mild spastic hemiparesis participated in the experiment on a voluntary basis. All participants were students from the Werkenrode Institute, where they followed an adapted education programme. Selection of the participants was based on several criteria. Participants needed to have functional sitting balance without adapted seating aids (on occasions a foot bench was used to enhance the stability of seating). All had normal or corrected-to-normal vision and hearing, no hemi-neglect, and displayed the behavioural and attentional capacities necessary to perform the experiment. We ensured that every participant could reliably grasp each of the three discs that were used in the experiment, with both the ipsi- and contra-lesional side. Likewise, we ensured that object distance was well within functional reaching distance. Table I presents additional participant information. All participants had undergone extensive rehabilitation programmes, and their situation was described as stable. Some participants received physical therapy, aimed at pain relief and preventing contractures. Neurophysiological data on the exact location of the lesion were not available because participants were students of the school for special education, rather than patients in a clinical or medical setting. Participants were naive about the exact purpose of the experiment. Before the experiment, all participants gave written informed consent. The study was approved by the local ethics committee and performed in accordance with the ethical standards laid down in the 1964 Declaration of Helsinki.

**Table I: Participant information**

| *Participant* | *Age (y:m)* | *Diagnosis* | *Condition* | *Other* |
|---|---|---|---|---|
| 1 | 17:3 | Right spastic hemiparesis | CP | – |
| 2 | 15:8 | Left spastic hemiparesis | CP | – |
| 3 | 18:2 | Right spastic hemiparesis | CP | – |
| 4 | 18:4 | Left spastic hemiparesis | CP | Epilepsy |
| 5 | 15:6 | Right spastic hemiparesis | CP | – |
| 6 | 18:3 | Left spastic hemiparesis | CP | Epilepsy |

TASK, APPARATUS, EXPERIMENTAL PROCEDURE, AND INSTRUCTIONS

We compared the control of prehension between the ipsi- and contra-lesional sides of the body in individuals with hemiparetic CP. Six young adults with mild hemiparetic CP performed unrestricted grasping movements to three discs that differed in size and which were placed at two different locations.

Participants were comfortably seated at a table. The task they had to perform consisted of grasping a disc, lifting it, and holding it in the air for approximately one second. The disc was placed in front of the participant on the table along the sagittal *y*-axis, at a close distance (150mm) or a far distance (300mm), both being within reaching distance of the participant (Fig. 1).

Round discs were chosen as targets, as previous research with this participant group indicated that they would have difficulties grasping an object in a normal way by using a precision grip (Steenbergen et al. 1998, 2000a). Also, these round discs afford more contact points compared with rectangular objects and, as such, the object did not force the participants to grasp it using a predetermined opposition axis. All discs were 30mm in height, and had diameters of 40, 60, and 80mm respectively. These disc sizes were chosen because previous research revealed distinct grasping patterns among them in participants without disabilities (Marteniuk et al. 1990) and because the largest disc size did not exceed the hand span of the participants. Participants were instructed to perform the grasping action at a comfortable speed. After a 'go' signal from the experimenter the participant could start the grasping action.

Three variables were manipulated: object size (40mm × 60mm × 80mm), object distance (150mm × 300mm), and hand used (unimpaired or ipsi-lesional × impaired or contra-lesional), resulting in 12 unique experimental conditions. In each condition, 10 consecutive trials were performed. Thus, each participant performed a total of 120 trials. Every participant started the experiment with the ipsi-lesional hand, because starting with their contra-lesional hand might have resulted in discouragement at the start of the experiment. Within each 'hand block', the six conditions were blocked according to object size (three conditions) and object distance (two conditions). The order of these six conditions was completely randomized across participants. The experiment took approximately 1 hour to be completed. Standard resting periods were introduced when a different object size was used (hence, two resting periods per hand), or at the participants' request.

A precalibrated Optotrak 3020 system (spatial resolution less than 0.01mm; Northern Digital, Waterloo, Canada.) was used for recording motion. Infrared light-emitting diodes were placed on the wrist, the thumb, and the index finger, as well as on the object. The three-dimensional position of these infrared light-emitting diodes was sampled in 'raw data' mode at a rate of 200Hz. Analyses of the data were performed off line. Concurrent with the Optotrak recording, video recordings were made to analyze the data qualitatively.

DATA ANALYSIS

Figure 2 shows representative examples of a velocity profile and an aperture profile. In this figure, some of the kinematic variables that were measured are displayed.

Raw data files were converted into three-dimensional coordinates, with the *y*-axis as the principal axis of movement (see Fig. 1). Data were filtered at 15Hz with a second-order dual-pass Butterworth filter. Subsequent analyses proceeded in three steps.

First, the temporal course of the prehension movement was determined by segmentation of the tangential velocity profiles. This was performed by using custom-made semi-automatic routines. The start of the movement was defined as the moment at which velocity of the wrist infrared light-emitting diodes exceeded 5% of peak velocity. The end of the movement was determined in two ways. First, the end of the 'free motion phase' (Steenbergen et al. 1998) was determined (termed 'reach end' in what follows) on the basis of

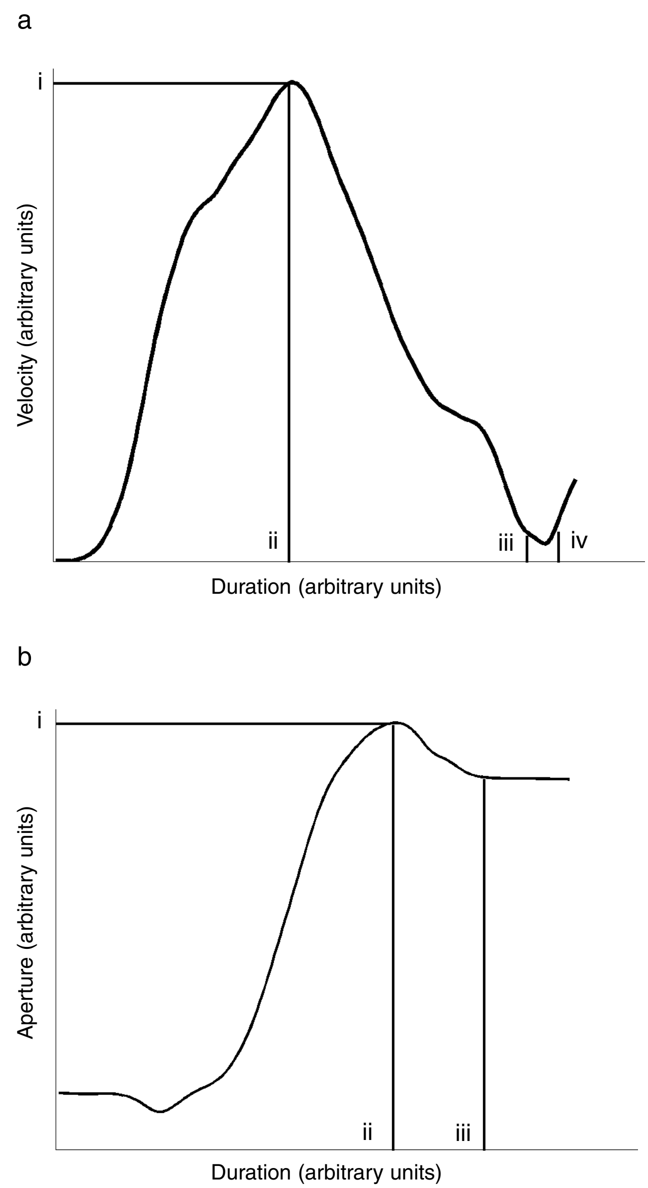


**Figure 2:** *Representative examples of a velocity profile and an aperture profile. Displayed in the (a) velocity profile are (i) peak velocity, (ii) time to peak velocity, (iii) reach end, (iv) and task end. In the (b) aperture profile are (i) peak aperture, (ii) time to peak aperture, (iii) and moment at which final hand orientation was determined.*

the velocity profile of the wrist. The reach end phase was defined as the first point in time at which wrist velocity declined to 5% of peak velocity after peak velocity. Second, the end of the complete task (termed 'task end' in what follows) was determined on the basis of the marker that was placed on the disc. The moment at which the velocity of this marker increased in the $z$-direction (i.e. object lift) was denoted the end of the task.

Second, the kinematic characteristics of the transport and grasp component were determined. The wrist infrared light-emitting diode was used to calculate the kinematics of the transport component. The following measures were calculated: peak velocity, time to peak velocity, skewness of the velocity profile (namely, time to peak velocity relative to movement time), and fluency of the transport movement. This last measure was determined by counting the number of time-normalized zero-crossings in the acceleration profile. For the calculation of the grasp component, the absolute three-dimensional distance between the infrared light-emitting diodes on the index finger and thumb was used. The following grasp variables were calculated: peak grasp aperture, time to peak grasp aperture, and skewness of the aperture profile (namely, time to peak aperture relative to movement time). To determine the temporal relation between the transport and grasp component, we calculated the time difference between the occurrence of peak aperture and peak velocity, both absolute and relative to total movement time.

Third, at the moment of object contact, we determined the final hand orientation by calculating the angle enclosed by the horizontal projection of the vector defined by the thumb and index finger, and the $x$-axis (see Figure 1). A smaller angle implies a more horizontal grasp in which the wrist is potentially more overextended.

For each dependent variable, the average for each condition pooled across replications was submitted to a repeated measures analysis of variance design with the following three within factors: object size (40mm, 60mm, 80mm) × object distance (150mm, 300mm) × hand used (ipsi-lesional, contra-lesional). Significance level was set to 0.05 and post hoc comparisons were performed using Newman–Keuls tests.

## Results

In Table II, values of all variables measured in the present study are reported as a function of object size, object distance, and hand used. A distinction is made between variables that were similar for both sides of the body and variables that were different for both sides of the body.

### 1. Temporal course of the movement

Two types of end of the movement, the reach end and the task end, are distinguished (see Data analysis section). Figure 3 displays the velocity profiles of the ipsi-lesional side (Figure 3a) and contra-lesional side (Fig. 3b). As can be observed from this figure, movement time of both hands differs marginally when assessed at 'reach end' (asterisks), but differs noticeably when assessed at 'task end' (open circles).

This was confirmed by the statistical analysis on both variables (see Table II). There was no significant effect of hand on the duration of the reach phase ($F[1,5]=4.03$, $p=0.10$). However, when movement duration was calculated on the basis of object lift (i.e. 'task end') there was a significant main effect of hand ($F[1,5]=7.05$, $p<0.05$). The contra-lesional hand needed significantly more time from the start of the movement to the lift of the object (1.45s) compared with the ipsi-lesional hand (1.01s). Thus, the timing differences between both hands started to occur after the wrist had reached the object. Finally, there was a main effect of object distance on both reach duration ($F[1,5]=65.28$, $p<0.001$) and total duration ($F[1,5]=33.26$, $p<0.01$). For both hands, reaching to objects placed at the far distance (300mm) resulted in a longer duration compared with

**Table II: Overview of variables measured as a function of object size, object distance, and hand used**

| *Variables* | *Object size* | | | *Object distance* | | *Hand used* | |
|---|---|---|---|---|---|---|---|
| | *Small (40mm)* | *Middle (60mm)* | *Large (80mm)* | *Near (150mm)* | *Far (300mm)* | *Ipsi-lesional (unimpaired)* | *Contra-lesional (impaired)* |
| Similarities between both sides of the body | | | | | | | |
| $Mt_{reach}$ (s) | 0.94 (0.18) | 0.96 (0.19) | 1.01 (0.22) | 0.87 (0.14) | 1.07 (0.19)$^c$ | 0.89 (0.18) | 1.05 (0.18) |
| PV (mm/s) | 685 (156) | 715 (180) | 716 (138) | 604 (102) | 807 (136)$^c$ | 710 (180) | 701 (133) |
| TPV (s) | 0.38 (0.06) | 0.39 (0.08) | 0.39 (0.08) | 0.36 (0.06) | 0.41 (0.07)$^a$ | 0.37 (0.07) | 0.4 (0.07) |
| PTPV (%) | 40.9 (4.2) | 40.9 (4.9) | 40.1 (6.3) | 42.4 (5.3) | 38.9 (4.3)$^a$ | 42.1 (4.9) | 39.1 (5) |
| PA (mm) | 72.3 (7.3) | 86.6 (8.4) | 103.7 (9.8)$^c$ | 87.4 (15.5) | 87.6 (15.5) | 85.2 (16.6) | 89.9 (14) |
| TPA (s) | 0.81 (0.22) | 0.83 (0.18) | 0.96 (0.31)$^a$ | 0.77 (0.19) | 0.97 (0.26)$^b$ | 0.77 (0.2) | 0.96 (0.26) |
| PTPA (%) | 90 (17.4) | 88.1 (7.3) | 95.8 (14.4) | 90.8 (15) | 91.8 (12.9) | 92.5 (14.4) | 90.1 (13.5) |
| PA–PV (s) | 0.42 (0.19) | 0.41 (0.12) | 0.51 (0.25) | 0.37 (0.17) | 0.53 (0.19)$^b$ | 0.38 (0.15) | 0.51 (0.22) |
| PA–PV (%) | 34.7 (6) | 38.2 (5.8) | 42.5 (8.3)$^b$ | 35.8 (6.7) | 41.1 (7.2)$^c$ | 38.9 (6.7) | 38.1 (8.1) |
| Opposition angle (deg) | 64.1 (4.9, 17.4) | 60.4 (4.2, 20.2) | 56.4 (3.7, 22.7)$^b$ | 62.6 (3.9, 20.1) | 57.9 (4.6, 20.2)$^b$ | 54.3 (3.8, 14) | 66.2 (4.7, 23.6) |
| Differences between both sides of the body | | | | | | | |
| $Mt_{total}$ (s) | 1.25 (0.48) | 1.17 (0.34) | 1.29 (0.41) | 1.11 (0.34) | 1.35 (0.44)$^b$ | 1.01 (0.23) | 1.45 (0.44)$^a$ |
| Fluency (amount) | 3.5 (2.5) | 2.9 (1.4) | 3.7 (2.4) | 3.6 (2.1) | 3.1 (2.2) | 4.3 (2.3) | 2.4 (1.4)$^a$ |

Values are means (average within-participant standard deviation). For variable opposition angle, values are means (average within-subject and between-subject standard deviation). $Mt_{reach}$, movement duration calculated from start to first contact with object; PV, peak velocity; TPV, time to peak velocity; PTPV, percentage time to peak velocity; PA, peak aperture; TPA, time to peak aperture; PTPA, percentage time to peak aperture; $Mt_{total}$, movement duration calculated from start to object lift.
$^a p<0.05$; $^b p<0.01$; $^c p<0.001$.

objects that were closer (150mm). In contrast, object size did not affect the temporal course of the movement, nor were any significant interactions found.

2. KINEMATIC CHARACTERISTICS OF THE TRANSPORT AND GRASP COMPONENT

*Transport component*

*Peak velocity.* There was no significant hand difference found for peak velocity. In a similar vein, peak velocity did not significantly differ across the three object sizes. In contrast, object distance did significantly affect peak velocity ($F[1,5]=105.51$, $p<0.001$). Peak velocity increased when grasping objects at the far distance (807mm/s) compared with objects at the near distance (604mm/s). The significant distance × size interaction revealed that peak velocity was largest for the middle-sized object at the far distance, and smallest for the large object at the near distance ($F[2,10]=4.70$, $p<0.05$).

*Time to peak velocity.* The only effect found for this variable was attributable to object distance ($F[1,5]=8.78$, $p<0.05$). Peak velocity was reached later when grasping the objects at the farthest distance (0.41s vs 0.36s).

*Skewness of the velocity profile.* Skewness of the velocity profile was determined relative to 'reach end'. A significant effect of object distance was shown ($F[1,5]=9.42$, $p<0.05$). Peak velocity was reached relatively later with objects placed at the closer distance (42.4%) compared with a farther distance (38.9%). No further effect was found for this skewness measure.

*Fluency of the movements.* The final measure of the transport component was fluency. The only effect found for this variable could be attributed to the hand used ($F[1,5]=9.07$, $p<0.05$). The number of zero crossings of the contra-lesional hand was almost twice that of the ipsi-lesional hand (4.3 vs 2.4).

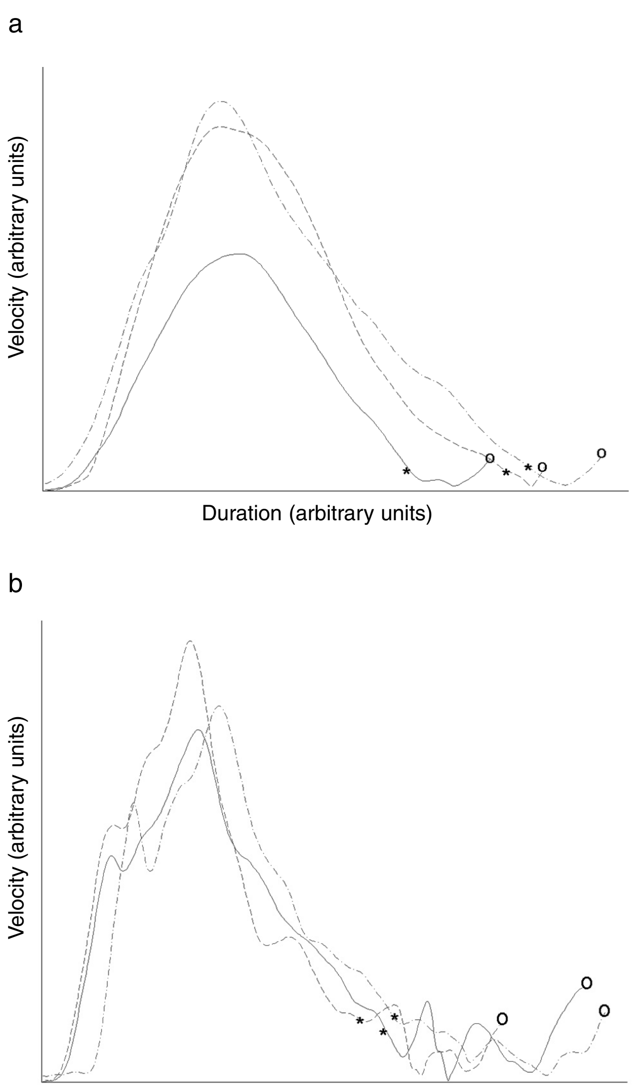


**Figure 3:** *Velocity profiles of transport component. (a) Velocity profiles of three individual trials for unimpaired hand (ipsi-lesional side). (b) Velocity profiles of three individual trials for impaired hand (contra-lesional side). *, reach end;* o, *task end.*

*Grasp component*

*Peak grasp aperture.* The only significant effect found for this variable could be attributed to object size ($F[2,10]=257.58$, $p<0.001$). Post hoc analysis of this effect showed that peak aperture differed for all three object sizes. Peak apertures ranged from 72.3mm (40mm object) to 86.6mm (60mm object) to 103.7mm (80mm object). Interestingly, and importantly, no main hand effect nor interaction was found for this variable. Hence, the increase in peak aperture relative to the increase in object size was present for both hands (Table II).

Marteniuk et al. (1990), studying a wide range of object sizes, described the relation between disc size and peak grasp aperture by the equation peak grasp aperture $=0.77$(disk size)$+4.89$, with a standard error of prediction of 16mm. It is obvious from this equation that object size is systematically overestimated. When applied to the disk size used in the present set-up, this equation yields peak apertures of 79.7mm, 95.1mm, and 110.5mm respectively. Although the average apertures we found are somewhat smaller (72.3mm, 86.6mm, and 103.7mm respectively), they fit well within the equation of Marteniuk et al. (1990) when the error of prediction is taken into account.

*Time to peak grasp aperture.* Participants reached peak aperture later in time when the object was placed at the far distance (0.77s vs 0.97s), as shown by a significant main object distance effect ($F[1,5]=34.11$, $p<0.01$). In addition, there existed a significant main effect of object size ($F[2,10]=5.42$, $p<0.05$). Post hoc analysis showed that time to peak aperture was not different between the small (0.81s) and medium (0.83s) objects, but increased significantly for the largest object (0.96s). No effect of hand was revealed on the time to peak grasp aperture.

*Skewness of the aperture profile.* As shown in Table II, peak grasp aperture occurred relatively late in the reach phase in all conditions (means ranging from 88.1 to 95.8%). Statistical analysis revealed no significant effect of object distance or object size on the skewness of the aperture profile, nor were any interaction effects found.

*Temporal order between transport and grasp component*

Results showed that all absolute time differences were positive, indicating that peak grasp aperture was consistently reached later in time than peak velocity. There was a significant effect of object distance on the time difference ($F[1,5]=28.65$, $p<0.01$). The absolute time difference between both measures was smaller when the object to be grasped was closer (0.37s vs 0.53s). Furthermore, the absolute time difference for the contra-lesional hand was larger (0.51s) than for the ipsi-lesional hand (0.38s), but this trend failed to reach statistical significance.

If the time difference between the kinematic peaks of transport and grasp component was considered proportional to total movement time, both hands displayed equal percentages (38.9% for the contra-lesional hand and 38.1% for the ipsi-lesional hand). Hence, the time difference between peak grasp aperture and peak velocity scaled to total movement time was unaltered between both hands. The main effect of object distance remained ($F[1,5]=37.01$, $p<0.0001$). Relative time difference for objects at the far distance was larger (41.1 vs 35.8%). Finally, a significant object size effect appeared ($F[2,10]=10.88$, $p<0.01$). Post hoc analysis showed that the relative time difference increased from small (34.7%) to middle (38.2%) to large objects (42.5%).

#### 3. FINAL HAND ORIENTATION

Statistical analysis showed a main effect of object size on the opposition angle ($F[1,5]=19.71$, $p<0.01$). All three object sizes differed from each other, from 64.1° to 60.4° to 56.4° (small, middle, large disc). Thus, the smaller the disc the more vertical the grasp with respect to the $x$-axis. In addition, we found a main distance effect ($F[1,5]=33.14$, $p<0.01$) as well as a significant hand × distance interaction ($F[2,10]=18.38$, $p<0.01$). Post hoc analysis of the latter interaction revealed that there was a significant decrease of opposition angle from close to far discs at the contra-lesional side (57.6° to 51°), whereas for the ipsi-lesional side there existed no significant decrease of opposition angle from close to far targets (67.6° to 64.9°). Finally, as shown in Table II, variations in opposition angle are large across all movement conditions, and no significant effect was found on the standard deviation of the opposition angle. We further established that the range of the average opposition angle per participant was large. At the ipsi-lesional side, average opposition angles in participants varied from 53.2° to 74.6°, hence a range of 21.4°. For the contra-lesional side we found even larger variations in opposition angle in participants, from 41.1° to 103.2°, hence a range of 62.1°.

Paulignan et al. (1997) reported opposition angles (here we took object position 0° [Paulignan et al. 1997], corresponding to the present set-up) from approximately 53° (small, 30mm), to 47° (60mm) to 44° (90mm). Thus, similar to the present results, there is a decrease in opposition angle (potentially more wrist extension) with an increase in object size. In contrast to the present findings, Paulignan et al. (1997) found smaller opposition angles (on average 12°), indicating that participants with hemiparesis make less use of wrist extension when grasping objects.

## Discussion

In the present study, we examined the control of prehension for both sides of the body in participants with spastic hemiparesis. Interestingly, the kinematics of both the transport and grasp components were strikingly similar between the ipsi- and contra-lesional sides of the body. Moreover, the invariances in the kinematics were the same as those that have been repeatedly reported in participants without disabilities (Jeannerod 1984; Marteniuk et al. 1987, 1990; Jakobson and Goodale 1991; Paulignan et al. 1991; Steenbergen et al. 1995). In addition, the effects of object distance and object size on the kinematics of the transport and grasp component are mostly in agreement with the early predictions stemming from Jeannerod's original visuomotor channel theory of prehension (Jeannerod 1981, 1984). According to this theory, the two components of prehension (transport and grasp) are exclusively controlled by extrinsic object properties (e.g. effect of distance and orientation on the transport component) and intrinsic object properties (e.g. effect of size and shape on the grasp component). However, several studies in controls without disabilities showed that these components interact (Marteniuk et al. 1987, Gentilucci et al. 1991, Kudoh et al. 1997) which may not, or possibly to a lesser degree, be the case for the participants of the present study. What may cause the exclusive influence of object properties (size and distance) on the transport and grasp component to 'reappear' in the group of participants with spastic hemiparesis?

To answer this question, we need to consider the optimization constraint that is used by the central nervous system for grasp planning. Studies on the macroscopic aspects of prehension in participants without neurological disorders have repeatedly shown that objects are initially grasped such that a comfortable posture is ensured at the end of the task (Rosenbaum et al. 1992, 1996; Short and Cauraugh 1997, 1999). In contrast, the results of recent studies suggest that participants with spastic hemiparesis optimize the start of a movement, and may use a step-by-step control strategy during the unfolding of the movement, without initially incorporating the end of the movement (Steenbergen et al. 2000b, 2004). Given these findings, we propose that these participants have difficulties with forward planning where the posture that the hand will attain at the end of the task is not taken into account when first taking hold of an object. Some of the present results may substantiate this assumption.

Participants reached peak aperture with both hands no earlier than at approximately 90% of total movement time (Table II). Hence, intrinsic object properties (size and shape of object) appear to have an effect very late in the prehension action. Typically, in participants without neurological disorders, peak aperture is reached after approximately 70% of the movement time (Marteniuk et al. 1990). Interestingly, the time differences between the kinematic peaks of transport and grasp component increased when a larger distance needed to be covered. This begs the question as to what extent the observed dissociation between transport and grasp component has a perceptual component. It may be assumed that these participants rely on visual feedback to monitor the movement of the arms more intensively, in order to counteract deficiencies in forward planning of the entire movement. Consequently, they do not focus on the properties of the target that needs to be reached. Corroborating this assumption is the present finding of a strong trend for larger absolute timing differences between peak velocity and peak aperture at the contra-lesional side. Indeed, it was shown previously that attention is almost exclusively focused on the contra-lesional hand during bimanual movement performance in this group (Steenbergen et al. 1996).

Most important, these combined findings suggest disorders in the process of forward planning in this group of participants (Hermsdörfer et al. 1999; Steenbergen et al. 2000b, 2004). Intrinsic object properties, such as size, are incorporated very late in the prehension action, and control proceeds in a step-by-step fashion. As such, it is not surprising that we found no consistent final hand orientation in the present study. The results showed that its standard deviation was large, both within and between participants, indicating that participants do not plan the end of the movement.

Despite the salient similarities in kinematics between both sides of the body, we found significant differences in both fluency of movement and total movement time. At the contra-lesional side, fluency was decreased. In a recent study, Van Thiel et al. (2000) showed an increase in path variability when fast hitting movements to stationary and moving targets had to be made (Van Thiel et al. 2002). Interestingly, this increased path variability did not hinder participants in adjusting their movements flexibly to the position and the velocity of the moving target. Potential mechanisms that may be held responsible for the increased variability are well known symptoms in spasticity, such as disturbances in agonist–antagonist inhibition (Hammond et al. 1988) and disturbances in the levels of co-contraction (Shumway-Cook and Woollacott 1995, Levin et al. 2000). These and the present findings suggest that the increased variability at the contra-lesional side may be a pathological constant, even in mild spastic hemiparesis.

As well as differences in fluency, large differences in total movement time were found between both sides of the body. Movement duration up to contact was similar between both sides of the body, but differences started to occur when total movement duration was regarded. Thus, differences between both sides of the body were present for the in-contact phase of the movement. In this phase, grip and lift forces are built up to securely grip the object for lifting. Deficiencies in the build up of these forces were shown previously in patients with hemiparesis (Eliasson et al. 1991). Clinically, it is known that after stroke the more proximal segments (trunk and shoulder) are less affected than the distal segments (hand and fingers). This may be a consequence of the hand being widely distributed in frontal and parietal cortical areas and, therefore, more vulnerable to lesions in these areas (Grichting et al. 2000). Neurophysiological studies suggesting that the distal musculature is controlled mainly from the contralateral hemisphere (e.g. Kuypers and Brinkman 1970, Brinkman and Kuypers 1973, DiStefano et al. 1980), combined with the present finding of increased time in contact with the contra-lesional hand, corroborate earlier findings (Steenbergen et al. 1998) suggesting that it is particularly the force regulation of the distal musculature that is disturbed at the contra-lesional side.

In the present study, we focused on group means and not on individual data. As neurophysiological data on the exact location of the lesion were not available, it was difficult to relate individual differences to damage of particular cerebral structures or severity of the disorder. To gain more insight into mechanisms of recovery after CP, as well as their significance for the control of motor tasks, necessitates the use of sophisticated brain imaging techniques (Thirumala et al. 2002). Using these techniques can be useful to identify areas, pathways, and mechanisms involved in motor recovery after CP. A potential mechanism for control that is suggested by the similar control of movement kinematics between both sides of the body may be the reorganization of the unaffected hemisphere after unilateral brain damage. Contemporary neurophysiological studies suggest that the unaffected hemisphere is reorganized after unilateral damage such that it is involved in the control of contra- and ipsi-lesional movements (Carr et al. 1993, Wasserman et al. 1994, Carr 1996, Turton et al. 1996, Netz et al. 1997). Based on these findings, we may speculate that the unaffected hemisphere could control both sides of the body, leading to the similarities in movement kinematics between the ipsi- and contra-lesional sides of the body that were observed in the present study. Certainly, these speculations need to be tested with brain imaging techniques.

We make a final point about the randomization technique used in the present study. To counteract potential demotivation of the participants, each of them started the experiment with the ipsi-lesional hand. This ordering may have influenced the performance of the contra-lesional side. Recently, it was suggested that training with the ipsi-lesional hand may help to form a template that may be used in the control of the contra-lesional hand as well (Utley and Sugden 1998, Steenbergen et al. 2003). This may have led to an increase in similarities between both sides of the body. However, this assumption could not be falsified by the present set-up, and it demands further study.

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